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Coherent ρ Production from Polarized Deuterium[1]

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Abstract: We discuss the coherent leptoproduction of vector mesons from polarized deuterium as a tool to investigate the evolution of small size quark-gluon configurations. Kinematic regions are determined where the final state interaction of the initially produced quark-gluon wave packet contributes dominantly to the production cross section. Two methods for an investigation of color coherence effects, which are appropriate for future experiments at HERMES, are suggested.

1 Scales in color coherence

High energy exclusive production processes from nucleon targets are determined by the transition of initial partonic wave functions to final hadronic states. Interesting details about such transition amplitudes can be obtained by embedding the production process into nuclei, where the formation of a particular final state hadron is probed interactively via the interaction with spectator nucleons (for a review see [1]).

In this context, we discuss the coherent photo- and leptoproduction of vector mesons from polarized deuterium at large photon energies $\nu \gtrsim 4\,GeV$:

$$\gamma^* + \vec{d} \longrightarrow V + d. \tag{1}$$

The corresponding amplitude can be split into two pieces: In the single scattering term only one nucleon participates in the interaction. This is in contrast to the double scattering contribution. Here the (virtual) photon interacts with one of the nucleons inside the target and produces an intermediate hadronic state which subsequently re-scatters from the second nucleon before forming the final state vector meson. At small $Q^2 \lesssim 1\,GeV^2$ exclusive vector meson production from deuterium is well understood in terms of vector meson dominance. In this framework the final state vector meson is formed instantaneously in the interaction of the photon with one

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of the nucleons from the target [2]. On the other hand, in the limit of large $Q^2 \gg 1\,GeV^2$ perturbative QCD calculations show that photon-nucleon scattering yields rather a small size, color singlet quark-gluon wave packet (ejectile) than a soft vector meson [3]. At high energies ν the final state interaction of such an ejectile with the second nucleon should differ substantially from the final state interaction of a soft vector meson. Therefore the magnitude of the final state interaction contains interesting informations about the initially produced ejectile and its evolution while penetrating through the target.

The ejectile wave packet and its propagation are characterized to a large extent by the following scales: The average **transverse size** of the ejectile wave packet, b_{ej}, which for the case of longitudinal photons is $\approx 4 \ldots 5/Q$ for $Q^2 \geq 5GeV^2$ for the contribution of the minimal Fock space component [4]. For these Q^2 it amounts to less than a quarter of the typical diameter of a ρ-meson ($\approx 1.4\,fm$). Furthermore the initially produced small quark-gluon wave packet does not, in general, represent an eigenstate of the strong interaction Hamiltonian. Expanding the ejectile in hadronic eigenstates one finds that inside a nuclear target all hadronic components, except the measured vector meson, are filtered out via final state interaction after a typical **formation time**: $\tau_f \approx 2\nu/\delta m_V^2$. Here δm_V^2 is a characteristic squared mass difference between low-lying vector meson states, which is related to the inverse slope of the corresponding Regge trajectory ($\delta m_V^2 \sim 1GeV^2$). If the formation time is larger than the nuclear radius, the ejectile will resemble an approximate eigenstate of the strong interaction while penetrating through the nuclear target. Therefore final state interaction should decrease with rising Q^2 at large photon energies. This phenomenon is usually called color coherence.

However the coherent vector meson production cross section, including its contribution from double scattering, is sensitive also to the **coherence length**: $\lambda \approx 2\nu/(m_V^2 + Q^2)$. The latter characterizes the minimal longitudinal momentum transfer $k_L \approx \lambda^{-1}$ required for the coherent production of the vector meson. (Here we omit the t-dependence of λ and k_L which is discussed in details in ref.[5].) Since the deuteron has to stay intact, one finds dominant contributions to the production cross section for $\lambda > R_d$, where $R_d \approx 4\,fm$ is the deuteron radius. Consequently vector meson production amplitudes from nucleons at a similar impact parameter but at different longitudinal positions will interfere and add up coherently. A decrease of the coherence length leads to a decrease of the coherent vector meson production cross section. Therefore if one investigates the double scattering contribution in different kinematic regions one should be careful in interpreting a variation of the final state interaction as a modification of the the ejectile wave function. First possible effects arising from a change in the coherence length have to be accounted for.

2 Single versus double scattering

In the single scattering contribution the vector meson is produced off one of the nucleons in the target, while the second nucleon does not participate in the interaction. The corresponding Born amplitude is determined by the vector meson production amplitude $f^{\gamma^* p(n) \to Vp(n)}$ from the proton or neutron, respectively, and the deuteron form factor S_d^j (where j indicates the dependence of the form factor on the target polarization):

$$F^{(1)} = f^{\gamma^* p \to Vp}(\boldsymbol{k}_\perp) S_d^j(-\boldsymbol{k}_\perp/2, k\_/2) + f^{\gamma^* n \to Vn}(\boldsymbol{k}_\perp) S_d^j(\boldsymbol{k}_\perp/2, -k\_/2). \qquad (2)$$

The presence of $k_- = k_0 - k_L$ in the form factors accounts for the recoil of the deuteron. If the target polarization is chosen perpendicular to the momentum transfer $\boldsymbol{k}$, at large ν only the difference of the monopole and quadrupole form factor, $S_d^j = S_d^0 - S_d^2$, enters in (2). In terms of the S- and D-components of the deuteron wave function these are $S_d^0(k) = \int_0^\infty dr\, j_0(kr)[u^2(r) + w^2(r)]$ and $S_d^2(k) = \sqrt{2}\int_0^\infty dr\, j_2(kr)w(r)[u(r) - w(r)/\sqrt{8}]$. It is important to realize that the monopole and quadrupole form factor are equal at $k = |\boldsymbol{k}| \approx 0.35\, GeV$. This generates a zero in $S_d^0 - S_d^2$ and consequently a node in the single scattering contribution to the vector meson production cross section at $t = t_d \approx -\boldsymbol{k}^2 \approx -0.5\, GeV^2$ [5] (see also the discussion of elastic hadron-deuteron scattering in ref.[6]). It should be emphasized that the latter is determined solely by the deuteron wave function and does not depend on details of the nucleon production amplitude, $f^{\gamma^* p(n) \to V p(n)}$. Thus we have identified a kinematic window where the single scattering contribution vanishes and the double scattering contribution can be investigated to high accuracy. A similar behavior of the single scattering amplitude can be achieved for a deuteron polarization along either $\hat{\boldsymbol{\kappa}} = (2\boldsymbol{q} + \boldsymbol{k})/|2\boldsymbol{q} + \boldsymbol{k}|$ or $\hat{\boldsymbol{n}} = \hat{\boldsymbol{k}} \times \hat{\boldsymbol{\kappa}}$, where $\boldsymbol{q}$ stands for the photon three-momentum. On the other hand, for an unpolarized deuteron target the sum of the monopole and quadrupole form factor enters in the Born amplitude. As a consequence the single scattering contribution always dominates the vector meson production cross section at moderate $-t \lesssim 1\, GeV^2$, leaving no favorable kinematic window for an investigation of final state interaction.

The double scattering amplitude stems from the final state interaction of an initially produced hadronic state. Expanding the latter in hadronic eigenstates h yields:

$$F^{(2)} \approx \frac{i}{2}\sum_h \int \frac{d^2\boldsymbol{k}'_\perp}{(2\pi)^2} S_d^j(\boldsymbol{k}'_\perp, k_-/2) f^{\gamma^* p \to hp}(\boldsymbol{k}_\perp/2 - \boldsymbol{k}'_\perp) f^{hn \to Vn}(\boldsymbol{k}_\perp/2 + \boldsymbol{k}'_\perp) + (p \leftrightarrow n). \tag{3}$$

The transfered momentum is split between both interacting nucleons. Therefore if the re-scattering amplitude of the ejectile $f^{hn(p) \to Vn(p)}$ is sizable, double scattering will be important in the region of moderate and large $-t \gtrsim 0.4\, GeV^2$.

In Fig.1 we show the differential cross section for the coherent ρ-production from deuterium polarized perpendicular to the momentum transfer,

$$\frac{d\sigma_d}{dt} = \frac{1}{16\pi}\left(|F^{(1)}|^2 + 2Re\left(F^{(1)*}F^{(2)}\right) + |F^{(2)}|^2\right), \tag{4}$$

calculated within vector meson dominance [5]. In this framework the double scattering amplitude accounts for the sizable re-scattering of the soft ρ-meson. The energy and momentum transfer are taken within the kinematic domain of the HERMES experiment. Figure 1 demonstrates that the minimum of the single scattering amplitude (at $-t \approx 0.5\, GeV^2$) is completely filled by final state interaction. Furthermore double scattering exceeds the Born contribution by a factor ~ 5 at $-t > 0.5\, GeV^2$.

3 Signatures for color coherence

Of course vector meson dominance is appropriate for small $Q^2 \lesssim 1\, GeV^2$ only. However we want to study the dependence of the final state interaction on Q^2 and ν to obtain informations on the ejectile wave function and its propagation through the nucleus. For this purpose we suggest

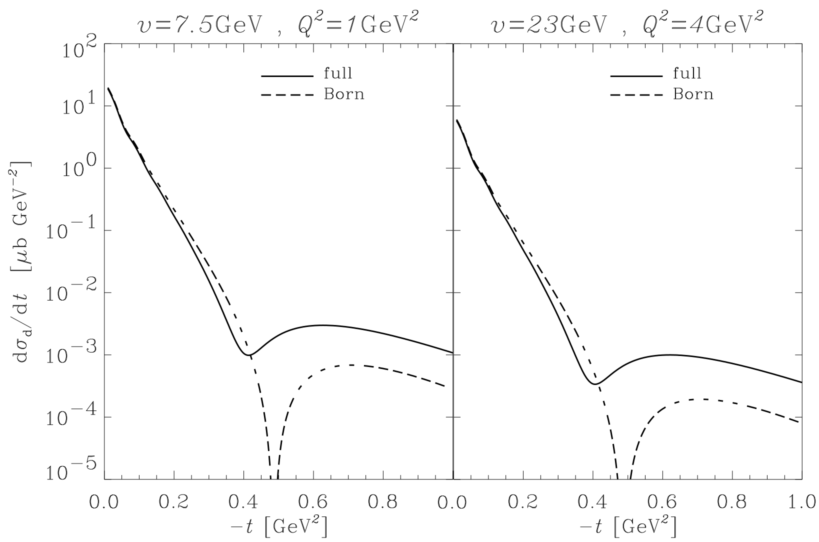

Figure 1: *The differential production cross section for coherent ρ-production from polarized deuterium for different values of Q^2 and ν. The target polarization is chosen perpendicular to the momentum transfer. The full line is the result for the production cross section within vector meson dominance. The dashed curve shows the Born contribution.*

investigations which are to a large extent independent on details of the ejectile production amplitude.

In this respect it is most promising to study coherent vector meson production from deuterium polarized perpendicular to the momentum transfer $\hat{\boldsymbol{k}}$ (or parallel to $\hat{\boldsymbol{\kappa}}$ or $\hat{\boldsymbol{n}}$) at $t \sim t_d$. Here the single scattering contribution to the cross section is very small and even vanishes at $t = t_d$ as discussed above. Exploring the production cross section in this kinematic window for different Q^2 and ν yields direct informations on the ejectile wave function. Since the transverse size of the ejectile shrinks with rising Q^2, perturbative QCD suggests that the vector meson production cross section should decrease and ultimately vanish at $t = t_d$ for $Q^2 \gg 1\,GeV^2$ and $\nu \gtrsim R_d\,\delta m_V^2/2 \approx 10\,GeV$. The latter requirement ensures that the formation time of the vector meson exceeds the deuteron size, $\tau_f > R_d$.

Furthermore Fig.1 demonstrates that in the domain of vector meson dominance ($Q^2 = Q_0^2 \lesssim 1\,GeV^2$) double scattering is by far dominant for $-t > 0.5\,GeV^2$: $\frac{(d\sigma_d(Q_0^2))/dt)_{full}}{(d\sigma_d(Q_0^2)/dt)_{Born}} \approx 5$. If final state interaction vanishes at large $Q^2 = Q_1^2 \gg 1\,GeV^2$ and large energies $\nu \gtrsim 10\,GeV$, we expect the above ratio to approach unity. Assuming that the Q^2-dependence of the initial ejectile production amplitude factorizes, and is approximately equal to the Q^2-dependence of the vector meson production cross section from free nucleons $d\sigma_N/dt$, we obtain:

$$\frac{(d\sigma_d(Q_1^2)/dt)_{full}}{(d\sigma_d(Q_0^2)/dt)_{Born}}\frac{(d\sigma_N(Q_0^2)/dt)}{(d\sigma_N(Q_1^2)/dt)} \longrightarrow 1. \tag{5}$$

In both cases it is important to keep the coherence length constant or to account for its possible modification.

4 Summary and Outlook

We discussed the coherent production of vector mesons from polarized deuterium as a tool to investigate the propagation of small size quark-gluon configurations, which are initially produced in high energy lepton-nucleon interactions at large Q^2. A kinematic window was found where the differential cross section stems only from contributions of the final state interaction of the ejectile. Two methods for an investigation of color coherence effects, which are appropriate for future experiments at HERMES, were proposed. Note that also the incoherent, diffractive production of vector mesons from polarized deuterium provides a variety of possibilities for detailed investigations of color coherence effects at HERMES [5]. Especially detecting the recoil nucleon from deuteron break-up yields a possibility to explore the evolution of small size quark-gluon configurations at different, well defined length scales.

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